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REPORT No. 268

FACTORS IN THE DESIGN OF CENTRIFUGAL TYPE INJECTION VALVES FOR OIL ENGINES

By W. F. JOACHIM and E. G. BEARDSLEY

REPRINT OF REPORT NO. 268, ORIGINALLY PUBLISHED JULY, 1927

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SUMMARY

This research was undertaken at the Langley Memorial Aeronautical Laboratory, at Langley Field, Va., in connection with a general study of the application of the fuel injection engine to aircraft. The purpose of the investigation was to determine the effect of four important factors in the design of a centrifugal type automatic injection valve on the penetration, general shape, and distribution of oil sprays.

The general method employed was to record the development of single sprays by means of special high-speed photographic apparatus capable of taking 25 consecutive pictures of the moving spray at a rate of 4,000 per second. Investigations were made concerning the effects on spray characteristics, of the helix angle of helical grooves, the ratio of the cross-sectional area of the orifice to that of the grooves, the ratio of orifice length to diameter, and the position of the seat. The sprays were injected at 6,000, 8,000, and 10,000 pounds per square-inch pressure into air at atmospheric pressure and into nitrogen at 200, 400, and 600 pounds per square-inch pressure. Orifice diameters from 0.012 to 0.040 inch were investigated.

It was found that decreasing the pitch of the helical grooves and thus increasing the centrifugal force applied to the spray increased the spray cone angle considerably, although the percentage increase was much less in dense air than in the atmosphere. On the other hand, the spray penetration decreased with increase in the amount of centrifugal force applied. About twice as much spray volume per unit oil volume was obtained with a high centrifugal spray as with a noncentrifugal spray. The spray cone angle increased, and the spray volume to oil volume ratio and spray penetration decreased with increase in the ratio of orifice area to groove area. Maximum spray penetration was obtained with a ratio of orifice length to diameter of about 1.5. Slightly greater penetration was obtained with the seat directly before the orifice.

INTRODUCTION

The centrifugal type injection valve is used to-day in a considerable number of oil-injection engines. Also, the centrifugal type oil burner, which employs the same principle, is used successfully with steam boilers burning fuel oil. In both cases the rotation of the oil is usually accomplished by passing it through helical grooves.

Oil sprays from injection valves, which depend entirely upon forcing the oil through small cylindrical holes to break it up, are finely atomized near the spray surface, especially at the spray tip, but have a core which is but little atomized. The possibility of obtaining more complete atomization and greater distribution of the oil particles by the use of centrifugal force has been studied by many investigators. (References 1 to 6.) The performance of engines operating with centrifugal-type injection valves often differs from that which was expected from observation of the sprays from these valves in the atmosphere. The explanation is presumably that the dense air of the engine cylinder has unexpected effects upon the sprays. Some knowledge of the behavior of centrifugal sprays in dense air should facilitate the successful application of this type of injection valve to engine service.

Computations have been made by several investigators of the penetration of single oil drops of small size when injected at high initial velocity into dense air. (References 1 and 2.) While these computations may show the approximate penetration of single oil drops, the behavior of sprays composed of millions of such drops is considerably different from that of single drops.

There are many variables in the design of a centrifugal injection valve and each variable may have a considerable effect upon spray characteristics. The purpose of this research was to investigate the effect of four important factors in the design of a centrifugal-type automatic injection valve upon the penetration, general shape, and distribution of oil sprays. The factors investigated were the helix angle of the grooves, the ratio of the cross-sectional area of the orifice to that of the grooves, the ratio of orifice length to diameter, and the position of the seat

A high-grade Diesel engine fuel oil of specific gravity 0.85 at 80° F. was used in all tests. It was injected at pressures of 6,000, 8,000, and 10,000 pounds per square inch into a chamber containing air at atmospheric pressure and nitrogen at pressures of 200, 400, and 600 pounds per square inch. The injection period was 0.003 second. The opening pressure of the automatic injection valve was maintained at 5,000 pounds per square inch throughout the tests.

Although the density of the gases in an engine cylinder seldom exceeds the density of air at room temperature and 250 pounds per square inch, the results presented cover a range of conditions permitting extended physical analysis. The effects of cylinder air temperature on the fuel spray may also lead to results comparable with those for the high chamber pressures.

This investigation was carried out at the Langley Memorial Aeronautical Laboratory of the National Advisory Committee for Aeronautics, at Langley Field, Va.

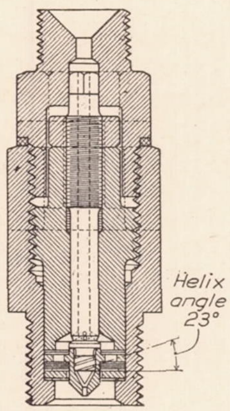


FIG. 1.—Diaphragm type automatic injection valve used with various stem and nozzle assemblies throughout this investigation

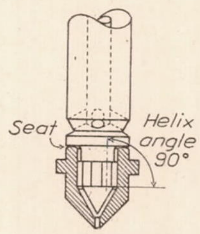


FIG. 2.—Stem with seat at top of nozzle

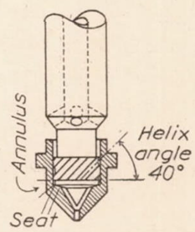


FIG. 3.—Stem with seat inside of nozzle

METHODS AND APPARATUS

The general method employed in this investigation was to record the development and cut-off of single sprays produced by an automatic injection valve, by means of special high-speed photographic apparatus capable of taking 25 consecutive pictures of the moving spray at a rate of 4,000 per second. Descriptions of the spray photography apparatus which was used for this work have been published by the National Advisory Committee for Aeronautics. (References 7 and 8.)

Cross sections of the assembled injection valve and of the two types of stem and nozzle used are shown in Figures 1, 2, and 3. A diaphragm-type automatic injection valve (Reference 8) was used for all tests and was fitted with the stem and nozzle which each test required. The type of stem and the nozzle used in all but one test are shown in Figure 2. The flat surface of the projecting ledge near the end of the stem seats on the V-shaped top edge of the nozzle. The other type of stem and the nozzle used are shown in Figure 3. In this case the stem seats on a 15° ledge inside of the nozzle. With the seat at the top of the nozzle the oil passed through the helical grooves after it passed through the seat. With the second seat position the pressure on the oil which passed through the grooves was not materially throttled until it reached the seat directly before the orifice. Table I gives the injection valve assemblies used in this investigation.

TABLE I

INJECTION VALVE ASSEMBLIES USED FOR INVESTIGATION OF EFFECT OF VALVE DESIGN

Assembly No.	Orifice diameter	Ratio orifice length to diameter	Groove helix angle	Number of grooves	Total groove area	Ratio orifice area to groove area	Nozzle seat position	Remarks
	Inch		°		*Square inch*			
1	0. 022	2	23	4	0. 00060	0. 63	Top	Effect of groove helix angle.
2	. 022	2	40	6	. 00060	. 63	do	
3	. 022	2	90	4	. 00060	. 63	do	
4	. 012	2	23	4	. 00060	. 19	do	(A) Effect of constant groove area. Effect of ratio of orifice area to groove area.
5	. 022	2	23	4	. 00060	. 63	do	
6	. 040	2	23	4	. 00060	2. 05	do	
7	. 022	2	23	4	. 00060	. 63	do	(B) Effect of constant orifice area.
8	. 022	2	23	4	. 00205	. 19	do	
9	. 022	2. 6	40	6	. 00060	. 63	do	Effect of ratio of orifice length to diameter.
10	. 022	1. 7	40	6	. 00060	. 63	do	
11	. 022	. 2	40	6	. 00060	. 63	do	
12	. 022	2	40	6	. 00060	. 63	do	Effect of seat position.
13	. 022	2	40	6	. 00060	. 63	Inside	

In order to obtain information concerning the actual spray characteristics, measurements were made of the spray images on photographic films. Time-penetration curves were plotted from data computed from these measurements taking into account the film speed and photographic reduction. Spray volumes were computed by summation of the volumes of a number of disks into which each spray was divided for volume measurements. It was assumed that the sprays were symmetrical in their cross sections.

RESULTS

EFFECT OF GROOVE HELIX ANGLE

The results of the tests in which the 90°, 40°, and 23° helical grooves were used are given in Figures 4 to 15. This range of groove angles gives at one extreme a noncentrifugal spray and at the other a high-centrifugal spray.

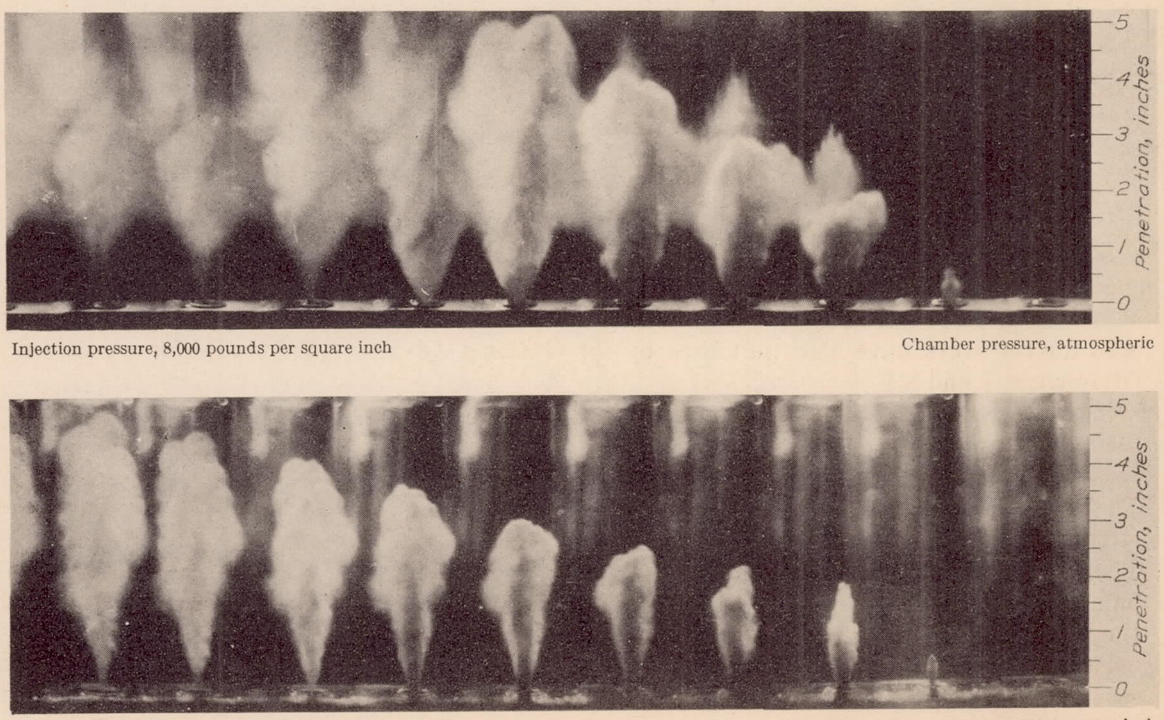
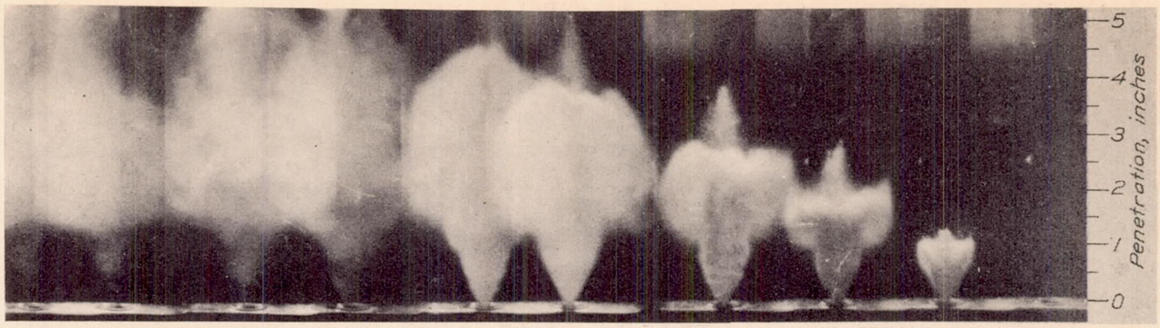
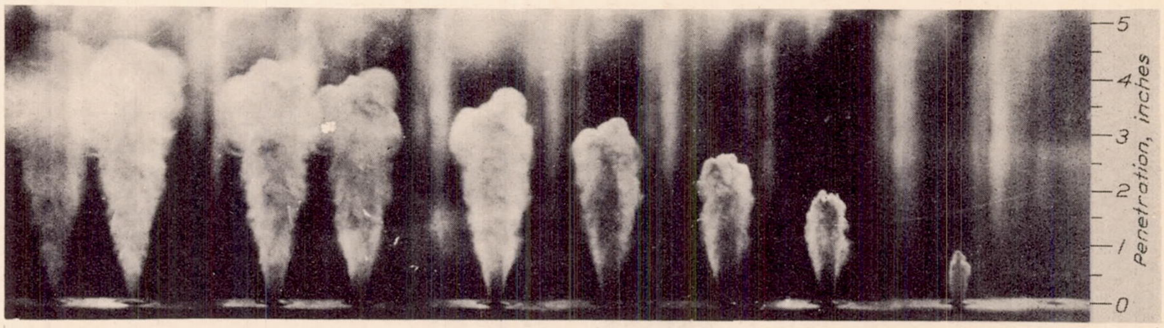


FIG. 4.—Spray photographs for stem and nozzle assembly No. 1, 0.022 inch diameter orifice, 23° helix and ratio of orifice area to groove area 0.63

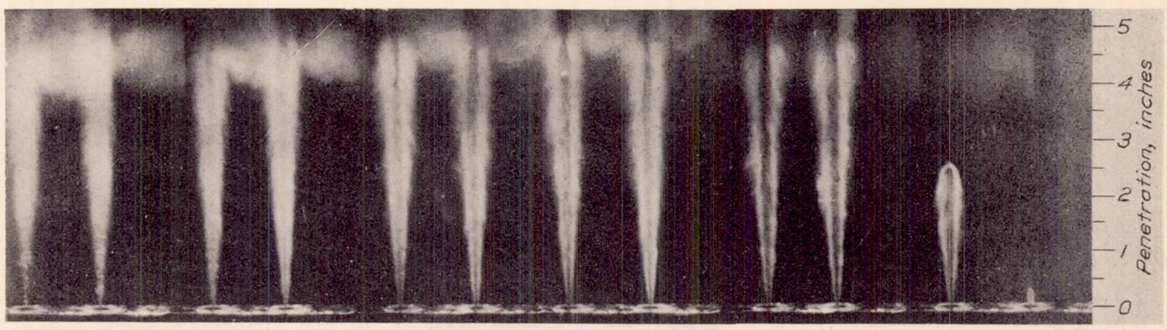


Injection pressure, 8,000 pounds per square inch — Chamber pressure, atmospheric

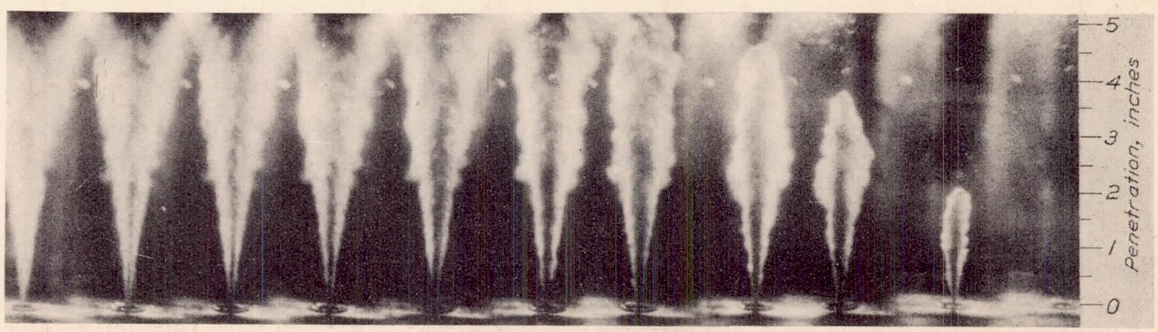


Injection pressure, 8,000 pounds per square inch — Chamber pressure, 200 pounds per square inch

FIG. 5.—Spray photographs for stem and nozzle assembly No. 2, 0.022 inch diameter orifice and 40° helix



Injection pressure, 8,000 pounds per square inch — Chamber pressure, atmospheric



Injection pressure, 8,000 pounds per square inch — Chamber pressure, 200 pounds per square inch

FIG. 6.—Spray photographs for stem and nozzle assembly No. 3, 0.022 inch diameter orifice and 90° helix

Figures 4, 5, and 6 are reproductions of actual photographs taken during the investigations. Each figure contains two series of pictures of the development of single sprays injected at 8,000 pounds per square inch pressure into atmospheric and into 200 pounds per square inch chamber pressure. The pointed sprays seen advancing ahead of the main sprays in

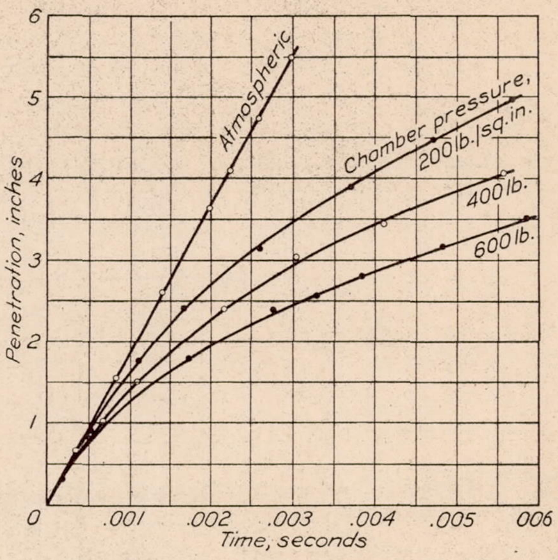


FIG. 7.—Effect of chamber pressure on spray penetration. Orifice diameter 0.022 inch. Groove helix angle 23°. Injection pressure, 8,000 pounds per square inch. Cut-off after 0.003 second. Stem and nozzle assembly No. 1

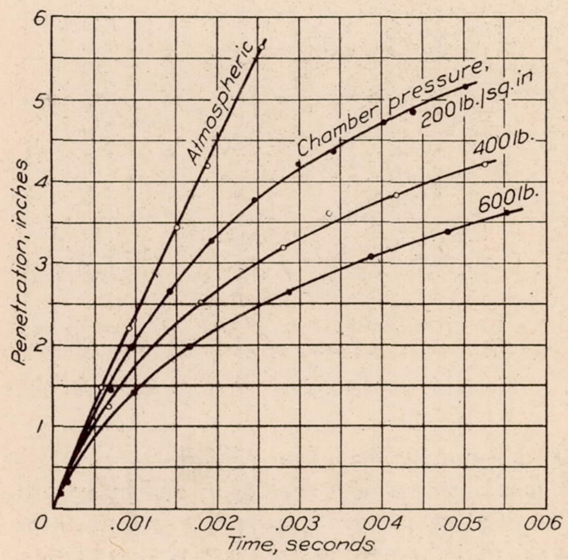


FIG. 8.—Effect of chamber pressure on spray penetration. Orifice diameter 0.022 inch. Groove helix angle 40°. Injection pressure 8,000 pounds per square inch. Cut-off after 0.003 second. Stem and nozzle assembly No. 2

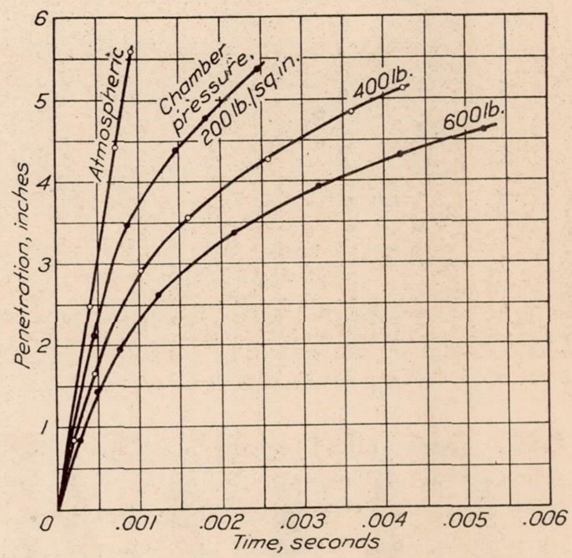


FIG. 9.—Effect of chamber pressure on spray penetration. Orifice diameter 0.022 inch. Groove helix angle 90°. Injection pressure, 8,000 pounds per square inch. Cut-off after 0.003 second. Stem and nozzle assembly No. 3.

Figures 4 and 5 are formed by oil trapped between the seat and the orifice which receives no rotation.

Figures 7, 8, and 9 are graphs showing the variation of penetration with time for a valve using each of the three-groove helix angles investigated, all other details of valve design and

of testing being maintained constant. The sprays were injected at 8,000 pounds per square inch pressure into the atmosphere and also into a chamber containing nitrogen at 200, 400, and 600 pounds per square inch pressures. Other pictures were taken using 6,000 and 10,000 pounds per square inch injection pressures and the four chamber pressures mentioned. In each case the penetration of the sprays increased with the injection pressure.

The effects of three-groove helix angles on the velocity and deceleration of the sprays in dense air at 200 pounds per square inch pressure are shown in Figures 10 and 11. Although the initial velocity of the sprays (fig. 10) was very much greater when the straight or 90° grooves were used, the velocity after 0.0025 second was the same for all three-groove angles. Thus the deceleration was more rapid for the spray produced with the straight grooves than for the 40° and 23° grooves, as is clearly shown by Figure 11. This rapid deceleration was accompanied by a rapid loss of kinetic energy by the spray. This energy presumably went

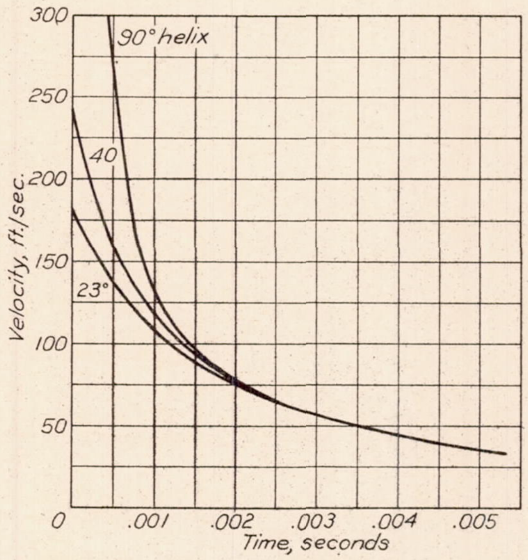


FIG. 10.—Effect of groove helix angle on spray tip velocity. Orifice diameter 0.022 inch. Injection pressure, 8,000 pounds per square inch. Chamber pressure, 200 pounds por square inch. Cut-off after 0.003 second. Stem and nozzle assemblies, Nos. 1, 2, and 3

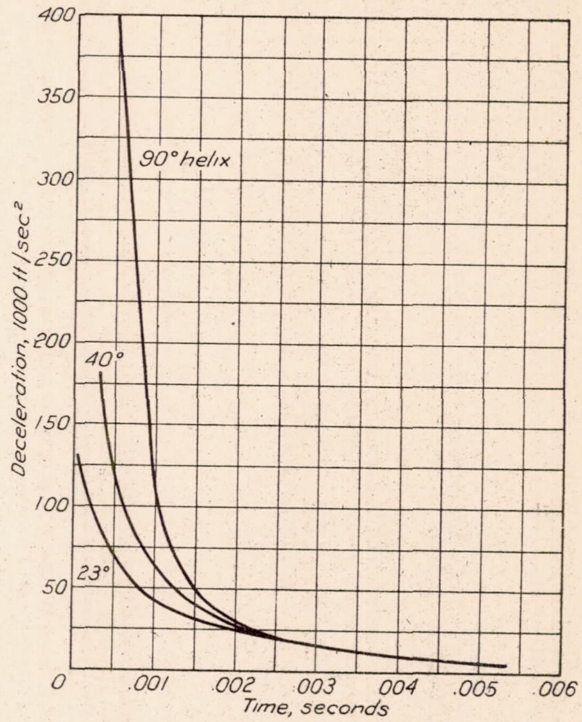


FIG. 11.—Effect of groove helix angle on spray tip deceleration. Orifice diameter 0.022 inch. Injection pressure, 8,000 pounds per square inch. Chamber pressure, 200 pounds per square inch. Cut-off after 0.003 second. Stem and nozzle assemblies, Nos. 1, 2, and 3

into breaking up and atomizing the spray and setting some of the surrounding gaseous medium into motion. The sprays from the 40° and 23° helical grooves were well atomized by centrifugal force as they emerged from the nozzle. The initial velocities of these sprays were therefore much less than that of the noncentrifugal spray, and the deceleration was also much less, because impact on the air did not cause much further atomization with the resultant rapid loss of energy.

The effects of the groove helix angle on the cone angle of the spray injected into the atmosphere and into nitrogen at 200, 400, and 600 pounds per square inch pressure are shown by Figure 12. The spray cone angle decreased with increase in the chamber pressure in the case of the high-centrifugal spray, while the spray cone angle of the noncentrifugal spray increased. In this latter case the spray was atomized and spread out by impact on the dense gas which resulted in the slightly increased spray cone angle. The curves indicate that the spray cone

angle would remain practically unchanged with a groove helix angle of about 80° for any chamber gas pressure, other conditions being the same as given in Figure 12.

The spray cone angle for 600 pounds per square inch chamber pressure was in the case of the high-centrifugal spray reduced to approximately one-half of the value attained for atmospheric pressure. This was because the oil particles thrown out centrifugally from the injection valve are extremely small and therefore have too little inertia to penetrate far into the dense gas. (Reference 2.) Thus the velocity of the oil particles at the outside of the spray falls to practically zero, while those near the core have a considerable forward velocity. The small clouds of oil particles appearing as bumps on the sides of the sprays (figs. 6 and 15) show no forward motion, and this fact seems to indicate that the other particles on the outside of the spray are practically at a standstill.

The volumes of spray produced by the same injection valve during equal elapsed time intervals and for the same test conditions but using three different groove helix angles are shown

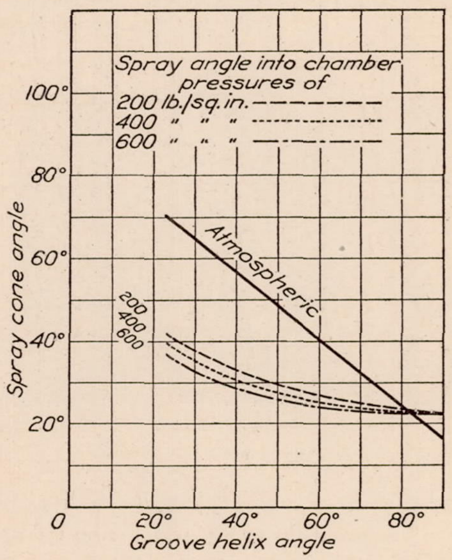


FIG. 12.—Effect of groove helix angle on spray cone angle of centrifugal sprays. Orifice diameter 0.022 inch. Injection pressure, 8,000 pounds per square inch. Cut-off after 0.003 second. Stem and nozzle assemblies, Nos. 1, 2, and 3

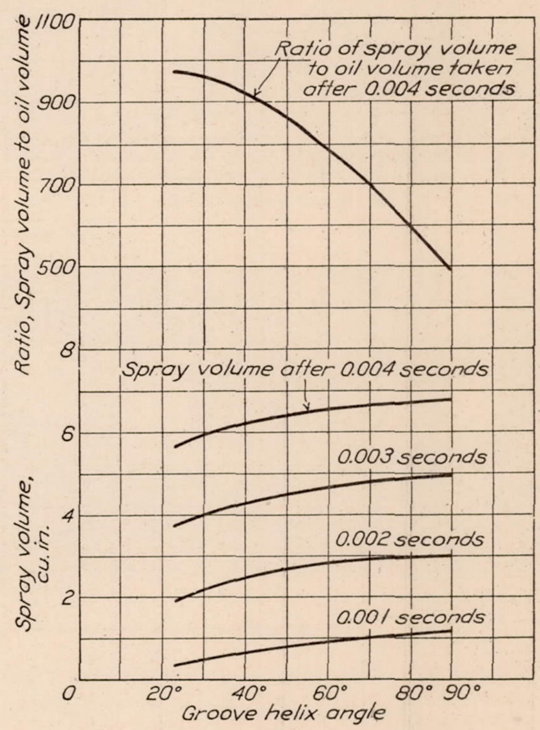


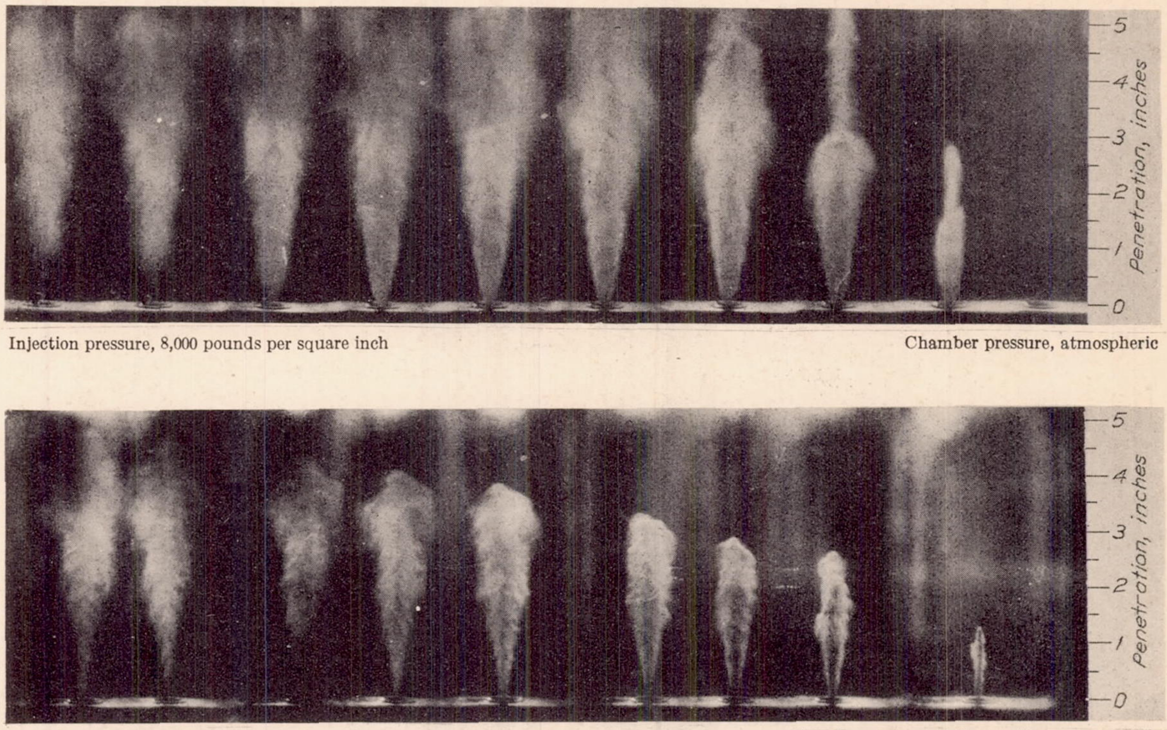
FIG. 13.—Effect of groove helix angle on spray volume, and ratio of spray volume to oil volume. Orifice diameter, 0.022 inch. Injection pressure, 8,000 pounds per square inch. Chamber pressure, 200 pounds per square inch. Cut-off after 0.003 second. Stem and nozzle assemblies, Nos. 1, 2, and 3

in Figure 13. The spray volumes increased with increase in the groove helix angle, but the volumes of oil, which produced each spray, also increased. In order to obtain a true measure of the spray distribution and possibly atomization, the ratio of the spray volume produced in a given time to the oil volume injected during that time must be considered. The curve at the top of Figure 13 shows the effect of groove helix angle on the ratio of spray volume to oil volume.

If it is assumed that a drop of oil one-fourth inch in diameter having a volume of 0.00817 cubic inch is injected from an injection valve such as was used in this investigation, the spray volume after 0.004 second would be, from Figure 13, approximately one thousand times the original oil volume, or 8.17 cubic inches. This would occupy about two-thirds the compression space of an engine of 5-inch bore by 7-inch stroke operating with a 12 to 1 compression ratio.

It is interesting to compare a drop of oil one-fourth inch in diameter with the spray, of volume equal to that of a sphere 2½ inches in diameter, which can be produced from it. The

outer surface of this sphere would be one hundred times that of the original oil drop. The spray would, however, be composed of millions of minute oil particles. The total surface area of a number of spheres of the same diameter and of a given total volume varies inversely as the sphere diameter selected. Also the diameter of the particles is inversely proportional to the cube root of the number of particles. Assume a particle diameter of 0.0004 inch (Reference 2), which would be one six hundred and twenty-fifth of the diameter of the ¼-inch drop. The total surface of all the oil particles would be six hundred and twenty-five times the surface area of a single ¼-inch drop and the number of particles the cube of 625, or slightly over 244,000,000. As the



Injection pressure, 8,000 pounds per square inch — Chamber pressure, atmospheric

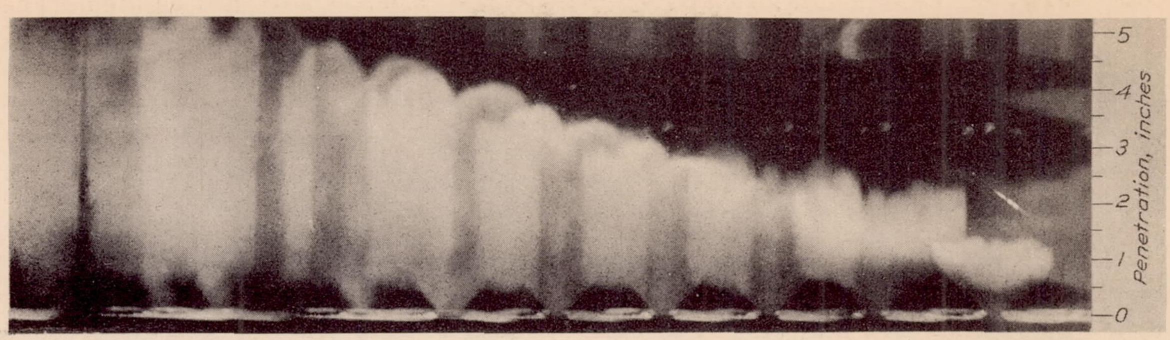
Injection pressure, 8,000 pounds per square inch — Chamber pressure, 200 pounds per square inch

FIG. 14.—Spray photographs for stem and nozzle assembly No. 4, 0.012 inch diameter orifice and 23° helix

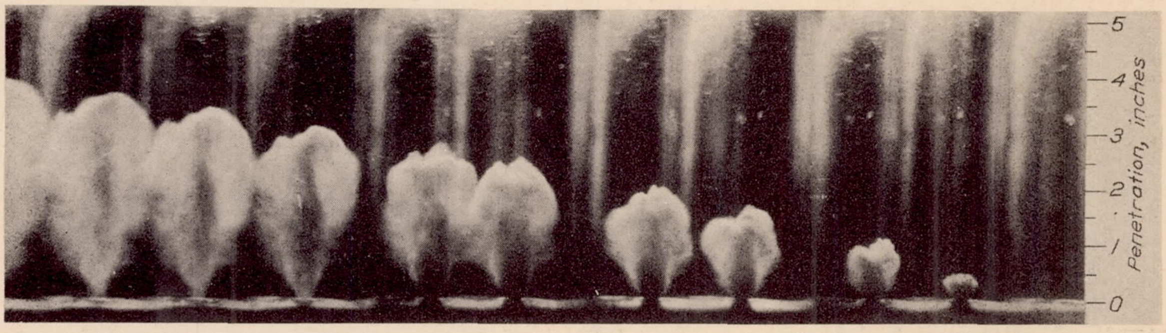
particle diameter approaches zero the total area and the number of particles will approach infinity. This discussion gives an indication of what it is possible to do with a small drop of oil by passing it through a centrifugal-type injection valve.

RATIO OF ORIFICE AREA TO GROOVE AREA

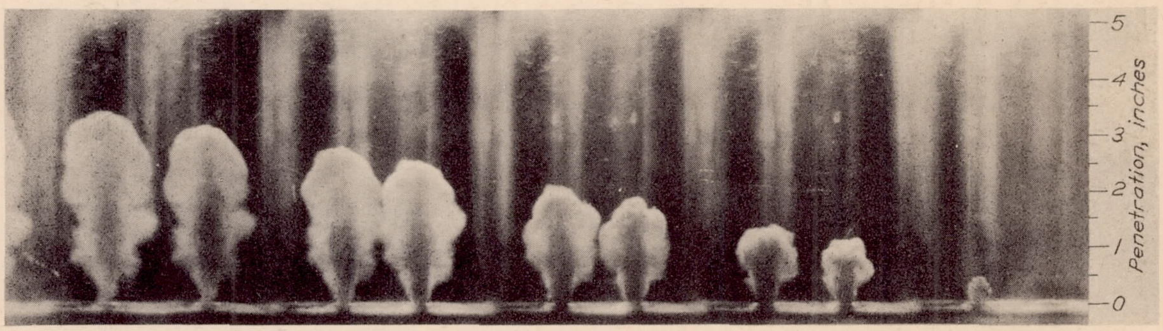
The results of the tests, in which the ratio of the cross-sectional area of the orifice to that of the grooves was varied from 0.19 to 2.05 are shown in Figures 14 to 20. The areas of the orifices controlled the flow with the first two ratios, while the area of the grooves controlled the flow with the third ratio. Figures 14 and 15 are series of pictures at two chamber pres-



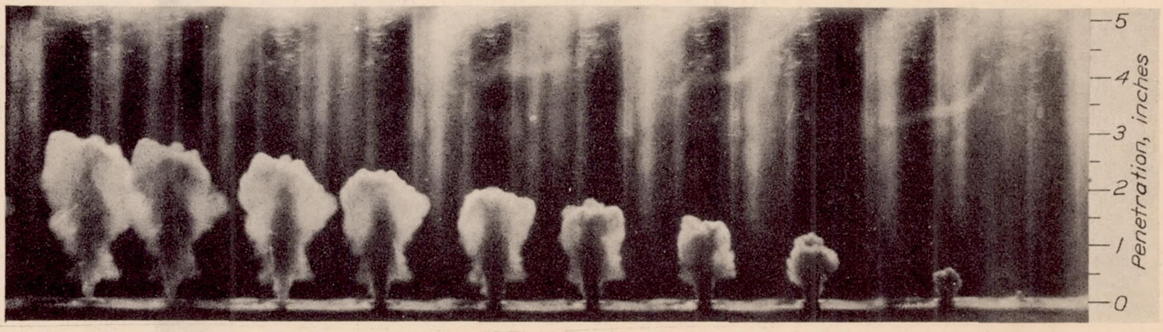
Injection pressure, 8,000 pounds per square inch Chamber pressure, atmospheric



Injection pressure, 8,000 pounds per square inch Chamber pressure, 200 pounds per square inch



Injection pressure, 8,000 pounds per square inch Chamber pressure, 400 pounds per square inch



Injection pressure, 8,000 pounds per square inch Chamber pressure, 600 pounds per square inch

FIG. 15.—Spray photographs for stem and nozzle assembly No. 6, 0.040 inch diameter orifice and 23° helix

sures using the same injection valve stem with large and small diameter orifices of such size as to give orifice to groove area ratios of 0.19 and 2.05. The time-penetration curves for the tests with these ratios are given in Figures 16 and 17. The pictures for the third ratio—namely, 0.63—have already been given in Figure 4 and the time-penetration curves in Figure 7.

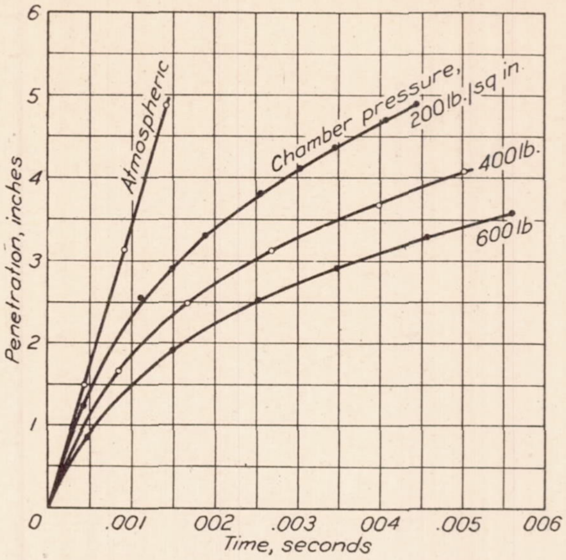


FIG. 16.—Effect of chamber pressure on spray penetration. Orifice diameter, 0.012 inch. Groove helix angle 23°. Injection pressure, 8,000 pounds per square inch. Cut-off after 0.003 second. Stem and nozzle assembly No. 4

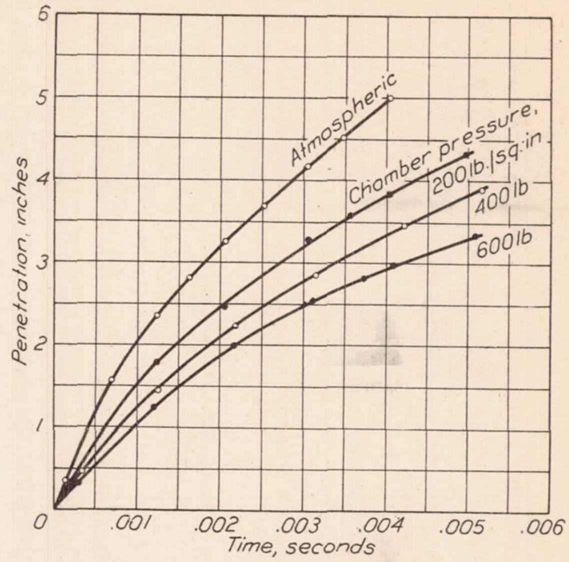
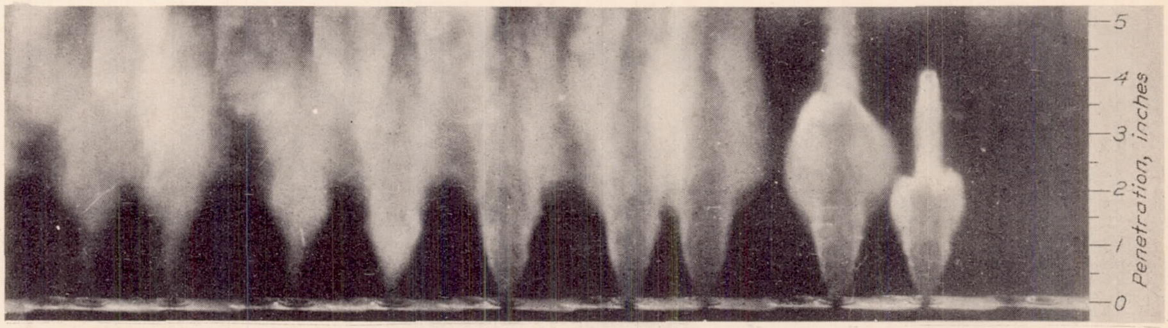
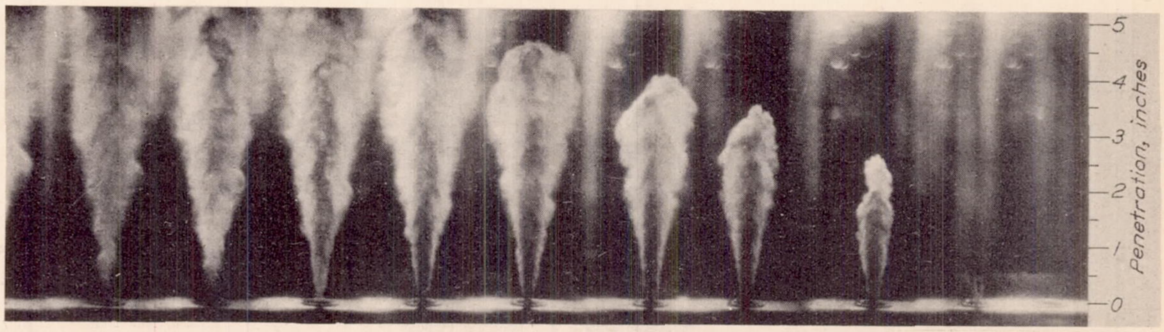


FIG. 17.—Effect of chamber pressure on spray penetration. Orifice diameter, 0.040 inch. Groove helix angle 23°. Injection pressure, 8,000 pounds per square inch. Cut-off after 0.003 second. Stem and nozzle assembly No. 6



Injection pressure, 8,000 pounds per square inch Chamber pressure, atmospheric



Injection pressure, 8,000 pounds per square inch Chamber pressure, 200 pounds per square inch

FIG. 18.—Spray photographs for stem and nozzle assembly No. 8, 0.022 inch diameter orifice, 23° helix and ratio of orifice area to groove area 0.19

In order to determine the effect of varying the orifice-groove area ratio by increasing the groove area, the orifice area was kept constant and the groove area was increased so as to change the ratio from 0.63 to 0.19. Thus the same ratio of 0.19 was obtained with two orifice diameters. A series of pictures for this test are shown in Figure 18.

The effect of the ratio of orifice area to groove area upon the spray cone angle and penetration in the atmosphere, after 0.002 second, is shown in Figure 19. The general trend of the spray cone-angle curve indicates that the spray cone angle would not be greatly increased by increase in the ratio of orifice area to groove area beyond 2.05. A narrow spray was obtained with the 0.012-inch orifice and ratio of 0.19. This was chiefly due to two causes. First, because the orifice area was very much smaller than the groove area, the velocity of the oil through the grooves was necessarily low. Thus the amount of centrifugal force applied to the oil passing through the orifice was small. Second, the small bore of the orifice did not allow much of the rotation of the oil to continue through it. Thus the spray emerging from the orifice was practically noncentrifugal. This fact accounts for the penetration being greater than that obtained with the larger orifices.

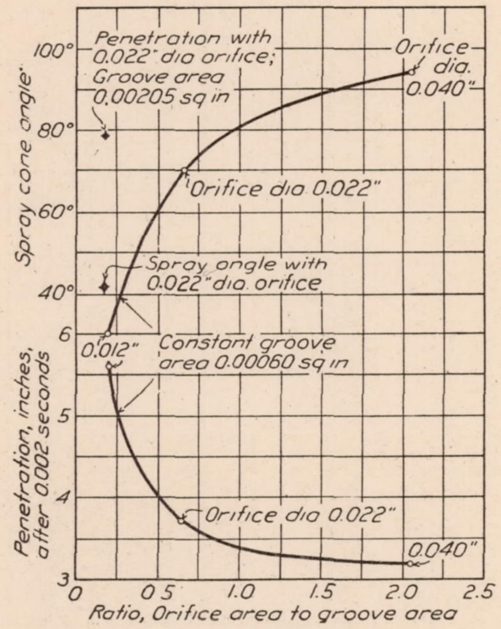


FIG. 19.—Effect of ratio of orifice area to groove area upon spray cone angle and penetration. Groove helix angle, 23°. Injection pressure, 8,000 pounds per square inch. Chamber pressure, atmospheric. Cut-off after 0.003 second. Stem and nozzle assemblies, Nos. 4, 5, and 6

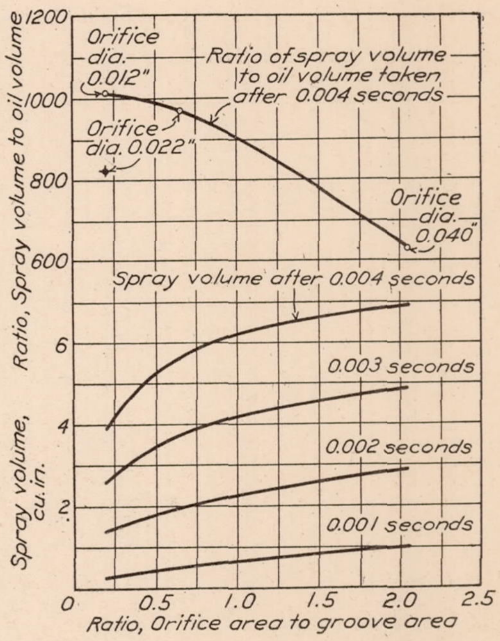


FIG. 20.—Effect of ratio of orifice area to groove area on spray volume, and ratio of spray volume to oil volume. Groove helix angle, 23°. Groove area, 0.00060 square inch. Injection pressure, 8,000 pounds per square inch. Chamber pressure, 200 pounds per square inch. Cut-off after 0.003 second. Stem and nozzle assemblies, Nos. 4, 5, and 6

The two points in Figure 19 labeled 0.022 inch, which are not on the curves, were obtained with a 0.022-inch orifice and ratio of orifice area to groove area of 0.19. The penetration was increased 50 per cent as compared with that for a 0.012-inch orifice and ratio of 0.19, and the spray angle was increased 30 per cent. The increase in penetration is explained by the greater inertia of the larger quantity of oil injected, and the increase in spray angle by increased jet rotation as a result of the larger orifice.

The effect of ratio of orifice area to groove area on the actual spray volume is shown in Figure 20. The quantity of oil injected increased with the ratio, so that the volume curves are not a measure of the spray distribution. The curve at the top of Figure 20 shows the variation of the ratio of spray volume to oil volume, with three ratios of orifice area to groove area. This curve gives an estimate of the relative spray distribution. The ratio of spray volume to oil volume for 0.19 ratio and 0.022-inch orifice is shown by a point below the curve. The spray distribution was not as great with the larger orifice and grooves as with the smaller orifice and grooves.

RATIO OF ORIFICE LENGTH TO DIAMETER

The results of the tests in which only the orifice length was varied, giving orifice length to diameter ratios of 2.6, 1.7, and 0.2, are shown in Figure 21. The same stem and nozzle were used in all three tests, the end of the nozzle being ground off to reduce the orifice length as desired for successive tests. This eliminated any variation in the sprays caused by slight differences in workmanship on similar nozzles.

The effects of the ratio of orifice length to diameter, on the spray cone angle and penetration after 0.003 second, in 200 pounds per square inch, chamber pressure, are shown in Figure 21. The spray angle increased with decrease in the orifice length. The shorter the orifice the less tendency it has to direct the spray axially and decrease the jet rotation because of friction. The result is, therefore, a larger spray cone angle. The spray angle seems to approach the angles of the stem tip and nozzle, both of which are 60°. (See fig. 2.) The maximum spray penetration is attained with a ratio of length to diameter of about 1.5. The decrease in penetration beyond this ratio may be caused by the reexpansion of the jet within the orifice which probably takes place with increased orifice length. This causes an increase in the cross section of the jet sufficient to fill the orifice at its outer end which produces an energy loss due to friction. The velocity is therefore reduced and likewise there is a decrease in the spray penetration.

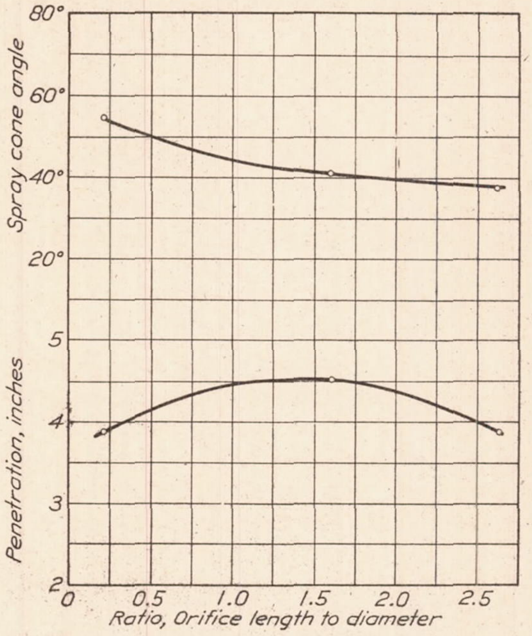


FIG. 21.—Effect of ratio of orifice length to orifice diameter on centrifugal sprays. Orifice diameter, 0.022 inch. Groove helix angle, 40°. Injection pressure, 8,000 pounds per square inch. Chamber pressure, 200 pounds per square inch. Cut-off after 0.003 second. Stem and nozzle assemblies, Nos. 9, 10, and 11

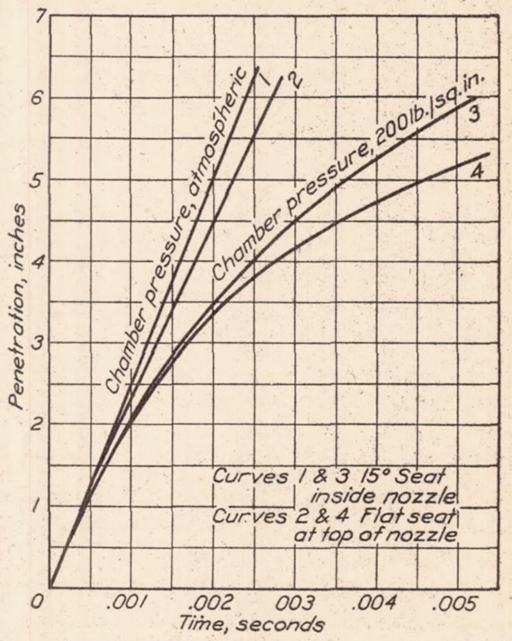


FIG. 22.—Effect of valve seat position on spray penetration. Orifice diameter, 0.022 inch. Groove helix angle, 40°. Injection pressure, 8,000 pounds per square inch. Cut-off after 0.003 second. Stem and nozzle assemblies, Nos. 12 and 13

EFFECT OF SEAT POSITION

The data presented in Figure 22 show that somewhat greater penetration was obtained with the injection valve stem seating on a ledge inside of the nozzle and directly before the orifice. The spray angle in the atmosphere was, however, decreased from 58° to 53°. It is probable that locating the seat directly before the orifice and after the helical grooves materially reduced the jet rotation produced by the helical grooves. This would tend to decrease the spray angle and increase the penetration. It is much easier and more economical to have the valve made with a flat seat, and much more accurately fitting surfaces are assured than if the seat is located inside of the nozzle.

CONCLUSIONS

This investigation has shown that although the application of centrifugal force to an oil spray does reduce the penetration, the spray may still maintain a relatively high degree of penetration into dense air. It has shown that examination of centrifugal sprays injected into the atmosphere may lead to incorrect conclusions as to their characteristics when injected into dense air.

The results obtained show that the penetration decreases with reduction in the pitch of the helical grooves, while the spray angle and distribution increase. The spray penetration and distribution increase with a reduction in the ratio of orifice area to groove area, while the spray-cone angle decreases. The spray-cone angle and penetration were increased, in the two tests made, by increase in the size of both orifice and grooves, keeping their ratio of areas constant. A ratio of orifice length to diameter of about 1.5 gave best penetration, although a smaller ratio gives a wider spray. Slightly greater penetration was obtained with the seat directly before the orifice, but the spray-cone angle was slightly less than with the seat at the top of the nozzle.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *January 27, 1927.*

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